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^{170}Er: The Search for Multiphonon Vibrations in a Rotational Nucleus[1]

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Abstract. To search for candidates for 2-phonon γ vibrations, ^{170}Er was studied with the inelastic neutron scattering reaction. The level scheme was extended using $\gamma\gamma$ coincidences and excitation functions. Spins were deduced from angular distribution measurements, and the Doppler-shift attenuation method (DSAM) was used to determine lifetimes.

Introduction

Single-phonon vibrations have long been a key feature of deformed nuclei and may be understood in the framework of the collective model [1], but it is only recently that candidates for multiphonon vibrations have been suggested in rotational nuclei. In particular, nuclei around ^{168}Er have been found to show evidence of double-γ phonon states [2]. However, the existence of such states remains a controversial subject and alternative explanations such as hexadecapole excitations have been offered [3].

Wu *et al.* [4] have searched this mass region for other nuclei exhibiting double-γ vibrations and ^{170}Er was suggested as a candidate. Younes *et al.* [5] have proposed a candidate for the $K^{\pi} = 4^{+}_{\gamma\gamma}$ state in ^{170}Er at 2.45 MeV based on data taken with the GEANIE array [6] at Los Alamos National Laboratory, and this work prompted a series of experiments at the University of Kentucky accelerator facility.

The discussion concerning the collectivity of these candidates being crucial to their assignment as multiphonon states, lifetime measurements for these levels are essential. With this in mind, a experiments to study ^{170}Er in greater detail were undertaken. With the (n,n$'\gamma$) reaction to excite the ^{170}Er nuclei, it is possible to determine lifetimes up to about 1 ps with DSAM.

The experiments

Nearly monoenergetic neutrons were produced using the ^{3}H(p,n) reaction from protons incident on a cell containing tritium. After inelastic neutron scattering on a sample of Er_2O_3 enriched to 96.88% in ^{170}Er, the γ rays emitted in the reaction were detected using HPGe detectors. In the coincidence experiment, the KEGS

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coincidence array [7] was used and the remaining experiments were performed with a single $> 50\%$ HPGe detector equipped with a Compton-suppression shield, which could be rotated around the sample. A level scheme was developed using a combination of excitation functions and $\gamma\gamma$ coincidences. The angular distribution experiments provided spins and Doppler-shift data for many states.

Unfortunately, at the excitation energy of the candidate state (2.45 MeV), the spectra are particularly complex and the $\gamma\gamma$ coincidences reveal the presence of a great many doublets and higher-order multiplets. Indeed, one of the two transitions (1518 keV), which depopulate the candidate state, is placed several times on the basis of the coincidence data. The remaining transition (1441 keV), however, does appear to be uncontaminated by other lines, and it is this transition which has been the focus of attention.

DSAM measurements

Data were taken at 11 angles ranging from 45° to 155° with respect to the incident proton beam, and the energies of the γ rays were precisely determined as a function of angle. Calibration was performed using ^{24}Na and ^{137}Cs radioactive sources, which were measured simultaneously with the in-beam data, and unshifted ^{170}Er lines, measured at a lower neutron energy with a ^{226}Ra source. The experimental F(τ) was extracted by fitting the observed γ-ray energies with the relation:

$$E_\gamma(\theta_\gamma) = E_0[1 + \beta F(\tau)\cos\theta_\gamma] \tag{1}$$

where β is the recoil velocity in units of the speed of light, θ_γ is the angle of the detector with respect to the direction of the incident neutrons, and E_0 is the unshifted γ-ray energy.

Theoretical F(τ) values are calculated using the Winterbon formalism [8] making it possible to extract lifetimes by comparing the theoretical and experimental F(τ) values. As a large (56 g) sample was used, corrections for absorption in the sample were applied.

A key advantage of inelastic neutron scattering with accelerator-produced neutrons is that it is possible to chose the neutron energy such that the state of interest is well populated, but that the feeding of the state from higher levels is negligible. Therefore, DSAM can often yield more accurate results than techniques which are more precise but suffer from unknown influences due to feeding.

Development of the level scheme

Given that one of the two γ rays depopulating the two-phonon candidate state is known to be a multiplet, it is important that the level scheme up to the candidate state be firmly determined to ensure that the other transition is really a singlet. To this end, an excitation function in 0.1 MeV steps was performed, as well as a $\gamma\gamma$ coincidence measurement at 3.4 MeV neutron energy. The combination of the two measurements proved essential in unraveling the complicated structure of ^{170}Er, and yielded a level scheme with over 200 placed γ rays. The 1518 keV transition from the double-γ phonon candidate to the 2^+ member of the γ band proved to be in a multiplet containing at least five γ rays, so the data from that γ ray cannot be used to extract any of the properties of the candidate state. The 1440 keV transition to the 3^+ member of the γ band, however, does appear to be a singlet.

Conclusion

Assuming that the 1440 keV transition is indeed a singlet, using the measured lifetime of 84^{+23}_{-37} fs and assuming that the branching ratio, which cannot be reliably determined from the experimental data owing to the complexity of the 1518 keV line, is close to that of ^{166}Er, a B(E2) value may be obtained. The ratio between the B(E2) value for the transition from the candidate to the 2^+ member of the γ band to that from the $2+_\gamma$ to the ground state is of the order of 3, slightly higher than the value of 2.78 from the harmonic vibrator model and significantly higher than the experimental value of 1.9 ± 0.5 for ^{168}Er [9] or the predictions of other models. It is possible that this discrepancy will be reduced by subsequent measurements, which are planned, and may yield an experimental branching ratio between the 1518 and 1441 keV states, if the experimental energy resolution can be improved.

This high value of the B(E2) ratio could also indicate a significant contribution from a hexadecapole vibration. It should be noted that QPNM calculations for ^{168}Er indicate that the $K^{\pi}_{\gamma\gamma}$ state at 2.06 MeV is in fact mostly (60%) a hexadecapole excitation and only 30% two-γ phonon excitation [10]. Similar calculations for ^{166}Er show that the corresponding state is mostly (73%) two-γ phonon excitation.

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